Towards an Operational Urban Modeling System for CBRN Emergency Response and Preparedness

Prepared by:
Pierre Bourgouin
Environment Canada, Dorval, Quebec

Scientific Authority:
Guy Jonkmans, 613-943-2504
DRDC Centre for Security Science

DRDC-RDDC-2014-C145
May 2014

IMPORTANT INFORMATIVE STATEMENTS

CRTI07-0196TD Towards an Operational Urban Modeling System for CBRN Emergency Response and Preparedness was supported by the Canadian Safety and Security Program (CSSP) which is led by Defence Research and Development Canada's Centre for Security Science, in partnership with Public Safety Canada. Partners in the project include Environment Canada, DRDC Suffield, Health Canada, J.D. Wilson & Associates, and CFB Halifax. CSSP is a federally-funded program to strengthen Canada's ability to anticipate, prevent/mitigate, prepare for, respond to, and recover from natural disasters, serious accidents, crime and terrorism through the convergence of science and technology with policy, operations and intelligence

Abstract

The objective of this project was to transition a state-of-the-science urban flow/dispersion modeling system, developed under CRTI Project 02-0093RD, towards the status of a functional operational system prototype at Environment Canada's Environmental Emergency Response Section (EC-EERS), a government operations centre. The proposed system will provide EC-EERS with the key-enabling technology to demonstrate its capability as a primary national reach-back and support centre for CBRN planning, real-time assessment, and emergency response in Canada.

To achieve this objective, this project implemented three principal components: (1) to provide additional advanced modeling capabilities, (2) to develop the required supporting infrastructure, and (3) to demonstrate the performance and applicability of the new operational system prototype. The first component significantly enhances the capabilities of the modeling system by incorporating thermal effects in the building-aware urban flow/dispersion models; improving the urban parameterization schemes used in the mesoscale flow models; and developing techniques for fusion of CBRN sensor data with model predictions for source reconstruction. The second component provides all the necessary supporting databases (e.g., 3D building data, land cover/land use classifications over Canadian cities, population distributions, CBRN source models, CBRN material and toxicological properties) to enable automated access to data required for an operational system. The third component demonstrates and exercises the operational system for a number of CBRN scenarios in different Canadian cities, including modeling in support of events of national significance (e.g., 2010 Winter Olympic Games in Vancouver, 2010 G8/G20 Meetings in Toronto).

The project deliverable was an integrated modeling system maintained in prototype mode within a government operations centre (EC-EERS), which can be used to generate unique CBRN operational dispersion modeling products and decision support aids. These products and capabilities have the potential to provide timely information and guidance to decision makers and emergency response managers at all levels of government to support the full spectrum of CBRN capability functions, such as pre-event scenario planning and preparedness, response, and post-event assessment.

This project was a success; the main objective of transitioning a state-of-the-science urban flow/dispersion modeling system towards the status of a functional prototype operational system at EC-EERS was fully accomplished. The project was also a success on other counts; not only all the milestones were completed (in some cases exceeding the initial scope) but also the project team has been very active to establish contacts with first responders or EMOs, therefore making sure the modelling system would be well positioned to be integrated into Canada's emergency response system. Furthermore, the project was on budget and only manageable delays occurred during the course of this complex project, as a result of careful planning.

Résumé

L'objectif de ce projet était d’effectuer la transition d'un système pour modéliser l'écoulement et de la dispersion en milieu urbain vers un statut de prototype opérationnel opéré par la Section de la réponse aux urgences environnementales d’Environnement Canada (EC-SRUE), un centre des opérations gouvernementales. Le système à la pointe du développement a été produit dans le cadre du projet IRTC 02-0093RD. Le système proposé donnera à la EC-SRUE une technologie clé permettant de démontrer sa capacité en tant que centre d’expertise et de soutien pour les d’événements CBRN au Canada : planification, évaluation en temps réel et interventions d'urgence.

Pour atteindre cet objectif, ce projet comportait trois composantes principales : (1) fournir des fonctionnalités supplémentaires de modélisation, (2) développer l'infrastructure nécessaire, et (3) démontrer l'efficacité et l'applicabilité du prototype opérationnel. La première composante améliore de manière significative les capacités du système de modélisation en intégrant les effets thermiques dans les bâtiments urbains, améliore les paramétrisations urbaine utilisées dans les modèles à la méso-échelle et développe une techniques de fusion de données de capteurs CBRN avec les prévisions du modèle pour la reconstruction de source. Le deuxième volet fournit toutes les bases de données nécessaires (par exemple, les données de bâtiments en 3D, les classifications couverture terrestre / terre pour les villes canadiennes et les propriétés toxicologiques des sources CBRN) afin de permettre un accès automatisé aux données requises pour un système opérationnel. Le troisième volet présente et exerce les capacités du système pour un certain nombre de scénarios CBRN dans différentes villes canadiennes, y compris la modélisation à l'appui des événements d'importance nationale (par exemple, Jeux Olympiques d'hiver à Vancouver en 2010, Réunions G8/G20 à Toronto).

Le livrable du projet est un système de modélisation intégrée maintenue en mode prototype par un centre des opérations du gouvernement (EC-SRUE), qui peut être utilisé pour générer des produits opérationnels spécialisés de modélisation de la dispersion de produits CBRN et des aides à la décision. Ces produits et ces capacités ont le potentiel de fournir rapidement des informations permettant aux décideurs et aux gestionnaires d'intervention d'urgence de soutenir l'éventail complet des besoins, tels que la planification de scénarios, la préparation, l'intervention et la post-évaluation des événements CBRN.

Ce projet a été un succès, l'objectif principal d’effectuer la transition du système de modélisation urbain de l'écoulement et de la dispersion vers un statut de prototype fonctionnel à la EC-SRUE a été pleinement accomplie. Le projet a également été un succès sur d’autres aspects; non seulement toutes les étapes ont été réalisées (dans certains cas dépassant la portée initiale), mais aussi l'équipe du projet a été très active pour établir des contacts avec les premiers intervenants ou les officiers d’urgence, s'assurant ainsi que le système de modélisation serait bien positionné pour s'intégrer dans le système canadien d'intervention d'urgence. En outre, le projet a respecté le budget et l’échéancier suite d'une planification minutieuse.

Table of contents

List of figures

Acknowledgements

This work was supported by Defence Research and Development Canada Centre for Security Science Chemical, Biological, Radiological/Nuclear, and Explosives Research and Technology Initiative (CRTI 07-0196TD). The partners involved in this project are:

The Environmental Emergency Response Section (EC-EERS) team, Meteorological Service of Canada (MSC), Environment Canada (EC)	Mr. Pierre Bourgouin, project manager Mr. Richard Hogue, project manager Dr. Najat Benboutat, Research scientist Mr. Nils Ek, Research Meteorologist Mr. Jean-Philippe Gauthier, Computer specialist Mr. Alexandre Leroux, Geomatics expert Mr. Gilles Mercier, Physical Scientist Mr. Serge Trudel, Computer specialist Mr. Calin Zaganescu, Research Meteorologist
The CFD team	Dr. Eugene Yee, Research scientist, DRDC-Suffield Dr. Kent Harding, Chief Scientist, DRDC-Suffield Dr. Fue-Sang Lien, Research scientist, Waterloo CFD Engineering Consulting Inc. (WatCFD)
The CMC-Dev team, CMC-Development Section, MSC-EC	Mr. Amin Erfani, Research Meteorologist Ms. Nathalie Gauthier, Research Meteorologist
The RPN team, RPN Science & Technology Branch, Environment Canada	Dr. Stéphane Bélair, Research Scientist Dr. Gilbert Brunet, Research Scientist Dr. Sylvie Leroyer, Research Scientist Dr. Jocelyn Mailhot, Research Scientist Dr. Syed Husain, Research Scientist Dr. Véronique Bouchet, Research Scientist
J.D. Wilson & Associates	Dr. John Wilson, Research scientist
Technical Assessments Coordination Section, Health Canada	Mr. Éric Pellerin, Nuclear Emergency Response Specialist
CFB Halifax Base	Lt (N) Darrell Benoit, Nuclear Emergency Response Officer
ESTD, EC, S&T Branch	Mr. Patrick Lambert, Emergency Response Specialist Dr. Carl Brown, Research Scientist
Regional environmental emergency response coordinator, Quebec Region, Environment Canada	Mr. Stéphane Grenon, Emergency Response Specialist
CRTI	Mr. Ian Summerell, RN Portfolio Manager

1 Introduction

There is an increasing concern over the possibility of a terrorist release of a CBRN agent in a large and densely populated urban area. To respond effectively to such an attack, rapid decisions need to be made concerning the transport, dispersion, deposition, and fate of the CBRN agent and its concomitant effects on the exposed population.

This includes the need to address the specific threat of atmospheric releases of hazardous materials, for real-time emergency response, pre-event planning, and post-incident assessment. Systems for predicting atmospheric dispersion can provide planners, first-responders, and public health officials with information on which to base life-and-death decisions. These include the delineation of safe zones for the establishment of incident command posts, sheltering-in-place or evacuation advisories, the need for protective equipment, and the utilization of hospital and health care resources.

Consequently, the ability to predict and track the dispersion of harmful agents has become a critical element of a nation's counter-terrorism planning, preparedness and response. The prediction from an atmospheric transport and diffusion model of a harmful agent's concentration, as a function of space and time, can be applied to a variety of purposes:

- Hypothetical releases at particular points and under various atmospheric conditions (planning scenarios) can be used by *planners* to identify potential zones of hazardous threats and to prepare effective responses for these scenarios.

- In an actual release situation, modeling of the incident as it evolves will provide critical information that will assist emergency *responders* in making critical decisions (e.g., immediate actions that are required to protect the health and safety of people exposed in the hazardous zones).

- Model predictions of concentrations are also important during the post-event phase to estimate the expected amount of deposited CBRN material. These predictions can assist in the interpretation of in-situ measurements of the contaminants (or in the aerial survey of an area with an RN detector). This type of support can extend into the recovery phase, which may last long after the immediate emergency.

Currently available modeling tools in the operational environment do not take into account the complexity due to buildings typical of major urban centers, and their effect on the flow. Higher-fidelity three-dimensional dispersion models, coupled to real-time observational data and numerical weather prediction model output, can fill this gap, and can be used for real-time response, and for provision of expert quality-assured predictions and refined assessments. This can be done by using 'building-aware' computational fluid dynamics (CFD) models that predict the complex flows in the urban environment, for both real-time response, as well as other types of applications (e.g. vulnerability analyses and planning studies).

The four year CRTI project 02-0093RD, which ended in March 2008, delivered a state-of-the-science urban flow/dispersion modeling system that explicitly addresses the capability gaps

identified above. The primary objective of project 07-0196TD was to transition the modeling system towards the status of a functional operational system prototype at Environment Canada's Environmental Emergency Response Section (EC-EERS), a government operations centre. The prototype will be referred to as the Canadian Urban Dispersion Modelling (CUDM) system and includes the meteorological cascade, the urban flow and the urban dispersion models. The proposed system will provide EC-EERS with the key-enabling technology to demonstrate its capability as a primary national reach-back and support centre for CBRN planning, real-time assessment, and emergency response in Canada.

To achieve this objective, this project implemented three principal activities:

1- provision of additional advanced modeling capabilities,
2- development of the required supporting infrastructure,
3- combining all the components in a quasi-operational computing environment and demonstration of the operational prototype system over a number of Canadian cities.

The project deliverable is an integrated modeling system maintained within a government operations centre (EC-EERS), which will have the potential to provide unique CBRN operational tools and services. These products and capabilities include the provision of timely information and guidance to decision makers and to the emergency response community.

2 Purpose

The primary objective of this project was to transition an enhanced version of the validated, state-of-the-science, multi-scale modeling system for the prediction of urban flow and dispersion of CBRN materials (developed and implemented under CRTI project 02-0093RD) towards the status of a demonstration operational system that is functional at a government operations centre (EC-EERS). This involved the full integration of the modeling system into the computational and communications infrastructure at EC-EERS.

A secondary objective of this project was to validate application of the operational modeling system to various CBRN scenarios over a number of Canadian cities (Vancouver, Calgary, Edmonton, Winnipeg, Toronto, Ottawa, and Montreal). To this end, specific CBRN scenarios were run over those cities in order to test and to demonstrate the capabilities of the operational modeling system prototype. This included demonstrating timeliness of provision of specific hazardous plume modeling products over Canadian cities for end-users (emergency managers and first responders), and Web and Internet-based software for rapid dissemination of advanced 3D flow and atmospheric dispersion modeling products and associated expert analyses from the operational response centre at EC-EERS.

3 Methodology

The project had three principal activities: (1) inclusion of additional advanced modeling capabilities, (2) acquisition of supporting data and development of tools required by the operational system infrastructure, and (3) combining all the components in a quasi-operational computing environment and demonstration of the operational system prototype.

The first activity involved developing and implementing the following new features:

1. Improvements in the urban parameterization scheme in the mesoscale model;
2. Incorporation of thermal effects in the building-resolving CFD model; coupling this capability with the thermal effects parameterized in the "urbanized" mesoscale flow model; and
3. Development of techniques for the fusion of CBRN sensor data with model outputs, for source reconstruction.

The second activity concerned the acquisition and development of the infrastructure required to transition the modeling system to a full operational status. This required the provision of supporting databases such as urban building data over major Canadian cities, databases of population distribution, hazard material source models for various CBRN release modes (e.g., improvised dispersion devices, sprayers, etc.), CBRN material and toxicological properties. This component also required computational efficiency enhancements of the urban flow and dispersion models through parallel algorithm development, and integration of the modeling system into the computational and communications infrastructure at EC-EERS.

The third activity involved demonstrating the operational system for a number of CBRN scenarios in various major Canadian cities, including participation in national-to-local exercises or in events of national significance (e.g., Vancouver 2010 Olympics, G8/G20 meetings, etc.). Various faults and weaknesses in the first version of the CUDM system were identified and corrected. Initial contacts with high-level users were made at the beginning of the project and various options were examined for the best way to communicate urban modeling information to users in an efficient and useful manner.

3.1 Inclusion of additional advanced modeling capabilities

3.1.1 Improvements in the mesoscale Numerical Weather Prediction (NWP) model

A new urban and land surface modeling system was included in a research NWP model to produced improved surface and near-surface meteorological fields. The system is based upon the Town Energy Balance (TEB) model for built-up areas, and on the Interactions between the Surface, Biosphere, and the Atmosphere (ISBA) land surface model for natural surfaces. It is driven by the operational CMC 15-km regional forecast model. Compared with the operational model, significant improvements were achieved with this system over urban and suburban sites. For example, the heat island effect as simulated by the research model was compared with that

forecast by the Canadian Meteorological Centre (CMC) operational 15-km Global Environmental Multiscale (GEM) model and higher-resolution 2.5-km GEM-Limited Area Model (GEM-LAM). The TEB-based model compared more favourably with remotely-sensed temperatures from the Moderate Resolution Imaging Spectroradiometer, for both urban and natural areas (Leroyer *et al*, 2011).

The TEB-based model was implemented into a version of the GEM-LAM model, which was then designated as urbanGEM. Several aspects of the urban model were improved during this project.

- The external version of the land surface modeling system has been completed and used to predict at 100-m grid spacing surface variables such as air temperature and winds. This new system was successfully used to predict urban heat islands over Montreal and Vancouver. It is expected to be transferred to full operations in 2013.

- Some improvements were made to physical processes important in cold weather such as what is experienced in most Canadian cities. Processes such as soil freeze / thaw and snow packs have been worked on in TEB.

- Treatment of vegetation inside urban canyons has been included in TEB, and is now ready to be tested.

- More complex canyon geometry (i.e., allowing asymmetric types of canyons, including streets and backyards), has been implemented and tested.

- Modifications were made to the diagnostics modules used to extract vertical profiles of meteorological variables (temperature, humidity, winds) in the urban canyons.

- A new approach to represent the exchange processes between the urban canopy and the atmosphere was coded. This new version of TEB is called the Canadian Multi-layer TEB (CaM-TEB). Based on this approach, the standard three-dimensional GEM was modified to include several atmospheric levels in the roughness sub-layer, in the urban canyons, going down to about 1 m or so above the street level. Results for IOP6 and IOP9 of the Oklahoma Joint Urban 2003 field experiment show improvement with the new approach for the representation of vertical profiles of low-level stability and winds. Of importance for urban dispersion applications, the new approach allows the prediction of meteorological variables within urban canyons (not possible in the previous implementation of TEB in GEM).

The urban meteorological modeling system was therefore much improved as a result of this project. In the next few years, further improvements should be achieved in CaM-TEB, including the inclusion of models specifically designed to represent building energy exchanges with the outside atmosphere, and road model.

3.1.2 Improvements in the CFD model

Enhancements to urbanSTREAM consisted of:

1. Inclusion of topographic capability to be able to consider effects of complex terrain on a flow.

2. Addition of calculation of thermal buoyancy effects.

3. Inclusion of passive tracer equation to model dispersion (urbanEU)

A surface temperature and heat flux simulator, urbanRAD, was developed to predict temperatures and heat fluxes on solid surfaces, based on local energy balance of heat and radiation exchanges.

The integrated system comprising the two-way coupling between urbanRAD, urbanEU and urbanSTREAM was validated with data from Intensive Observation Period Six (IOP6) of the Joint Urban 2003 Oklahoma City field experiment. Two wind libraries were built, one for Vancouver and the other for Toronto in support of emergency response applications (requiring quick turn-around times) for the 2010 Winter Olympic Games and for the 2010 G8/G20 Summits in Toronto. In total, up to 64 wind directions were considered in the libraries.

3.1.3 Development for source reconstruction

An operational implementation of an innovative sensor-driven modeling paradigm for source reconstruction has been realized in the form of a software module, urbanSOURCE. This module permits the rapid and robust estimation of the parameters of an unknown source, using a finite number of noisy concentration measurements obtained from a CBRN sensor array, and includes a rigorous determination of the uncertainty in the inference of the source parameters. The probabilistic inferential methodology in urbanSOURCE has been successfully validated using concentration data measured in a real urban environment (Joint Urban 2003 field experiment conducted in Oklahoma City, Oklahoma), involving transport and dispersion of an agent on an urban-industrial complex scale and in a complex terrain environment involving transport and dispersion of an agent on a continental scale (European Tracer Experiment). UrbanSOURCE can be used potentially with any computer program that provides estimates of the source-receptor sensitivity field (or, equivalently, the conjugate concentration field C^*), which provides the physics-based mapping from concentration measurements made at a receptor and the source characteristics at the source. Although urbanSOURCE has been specially designed to enable source (event) reconstruction in the complex urban environment (where the source-receptor sensitivity field can be obtained using urbanAEU), it can also be used over open and complex terrain where buildings are absent.

Towards this purpose, it should be noted that a recent successful application of urbanSOURCE involved the source term estimation of an “unknown” source from information provided by very limited radiological (concentration) measurements obtained using 3 radiological detectors that formed part of a network of 40 radiological detectors that has been set up as a verification tool for the Comprehensive (Nuclear) Test Ban Treaty (CTBT). The 3 detectors were located at St. John’s, Newfoundland, Charlottesville, Virginia, and Ashland, Kansas. Using sensor-receptor

sensitivity fields provided for these 3 receptor locations from re-analyzed meteorological information, urbanSOURCE successfully provided source term estimates of the both the location and emission rate of the “unknown” source (suspected to be daily releases of radiological isotopes from Chalk River Laboratory near Ottawa, Ontario). This is the first demonstration of the utility of urbanSOURCE for event reconstruction using real-world concentration measurement obtained from a real-world sensor network (as opposed to field trial data used in the validation of the Bayesian inference engine).

The operational implementation of source reconstruction with urbanSOURCE would enable the rapid estimation of an unknown source term associated with a covert (clandestine) release of a CBRN agent, using the available concentration data measure in real-time by a sensor network, followed by a an accurate and timely prediction of the agent’s spread and deposition required for making more informed decisions for mitigation of the consequences of the toxic release. The capability provided by urbanSOURCE provides the inextricable linkage of CBRN sensor data with advanced models for atmospheric dispersion (and, more particularly, for urban dispersion), leading potentially to significant improvements in the situational awareness in the battle space.

To complete the development effort for provision of tools for source reconstruction begun here, the software developed needs to be interfaced with information (warning and reporting) systems for automated data acquisition from CBRN sensor networks, and with the capability to provide the concomitant automated computation of source-receptor sensitivity (SRS) fields associated with the concentration data, taking into account uncertainties in the background meteorology and other uncertain parameters used in determination of these SRS fields (viz., accounting properly for potential sources of model uncertainty which needs to be properly characterized for a successful application of the source reconstruction paradigm embodied in urbanSOURCE). It is anticipated that the incorporation of these capabilities into a government operations facility will give it the key-enabling tools to provide expert quality-assured sensor-driven CBRN hazard predictions (obtained using data fusion or data assimilation) and concomitant decision-support aids which can form the basis for making significantly improved decisions for responding to and mitigating hazardous releases, as well as providing more timely and prescient response guidance.

3.2 Development of supporting data and tools required by the operational system infrastructure

All the components of the CUDM system (the meteorological cascade, the CFD model urbanSTREAM, the urban dispersion model urbanLS) were to be integrated using SPI. SPI is an application developed by EC-EERS which provides an ideal framework to integrate all the other components and sub-components to form a truly integrated system. SPI also provides a graphical interface to execute CUDM pre-processing and launch the suite’s models. SPI is an important component to bring the prototype into the operational world.

Sustained efforts were needed to acquire and process digital building databases for most of the major Canadian cities due to the lack of standardization, each city having its own internal organization, protocol and format. These data are necessary to run the building-aware modules of the CUDM system.

Urbanized meteorological NWP models (urbanGEM) need high spatial resolution urban land use and land cover (LULC) classification for Canadian cities. It is also used to produce specific parameters required by TEB. A module called UrbanX was developed for automatically generating these fields from different geospatial databases (CANVEC, vegetation DB, etc.). UrbanX supports hundreds of geospatial data file formats and seamlessly manage geographical projections and datum.

Specialized visualisation tools were developed for operational meteorologists to examine high-resolution meteorological outputs from the improved weather forecast from urbanGEM. These tools were used during the prototype test period covering the 2010 Vancouver Olympic Games and during the G8/G20 meetings.

3.3 Demonstration of the CUDM prototype

The demonstration of the prototype followed the following steps:

1. Acquire building databases for the main Canadian cities, which are necessary to run urbanSTREAM and urbanLS.

2. Produce the CUDM system, a unified suite from modules developed by different groups, having different coding standards, under SPI.

3. Test this first version of the CUDM system with a limited series of cases, to develop a prototype with a minimal level of usability, efficiency and robustness, in time for the Vancouver 2010 Olympics and Paralympics Games.

4. Develop specialized visualisation tools for operational meteorologists to examine high-resolution meteorological outputs from urbanGEM.

5. Contact operational meteorologists involved in the provision of forecasts during the Olympics from the Pacific Storm Prediction Centre (SPC) in order to obtain their feedback regarding the quality of urbanGEM, the urbanized meteorological model, during the Games.

6. Test the CUDM system extensively during the 2010 Olympics and Paralympics, by running it in an automated forecast mode for several weeks, and use the findings to improve the system.

7. Run the system in automated forecast mode for a second extended testing period during the G8/G20 2010 meetings in Toronto. Contacts were made prior to the beginning of the meetings with operational meteorologists involved in the provision of forecasts from the Ontario Storm Prediction Centre in order to provide feedback regarding the quality of urbanGEM. Again, findings from this second experiment will serve to upgrade the system.

8. Run the CUDM system in automated forecast mode over Montréal, Ottawa, Winnipeg and Calgary. These experiments were used to test alternative configurations, including different truncated NWP cascades. The truncation speeds up the execution time at the cost of losing the higher resolution meteorological inputs to urbanSTREAM. This approach could be used to rapidly produce an initial guidance, which would be refined later.

9. Make the necessary adjustments or corrections to the system. At the end of this process, the CUDM system should be sufficiently well-adjusted to be quasi-operational.

10. Throughout the steps, meet potential interested users to refine CUDM products in response to their needs

Running the CUDM system for extended periods ensured that the prototype would be subjected to a variety of different meteorological scenarios, testing its flexibility and robustness under many different wind flow conditions. Necessary corrections and adjustments were applied to problems that were unlikely to have been discovered from a small number of runs.

3.3.1 Overview of the CUDM system

Figure 1 gives a schematic of the complete CUDM system. Larger scale environmental flow is computed in a cascade of increasingly high-resolution numerical weather prediction (NWP) models (Figure 2), finishing with the mesoscale model urbanGEM. The wind forecast from one of the models in the NWP cascade is input to the CFD model urbanSTREAM, which generates the urban wind flow at the building-street scale. The resulting urban flow is passed to the urban atmospheric dispersion model, urbanLS, which calculates the dispersion and average concentrations resulting from prescribed release scenario. All these components are combined using SPI to form an integrated tool.

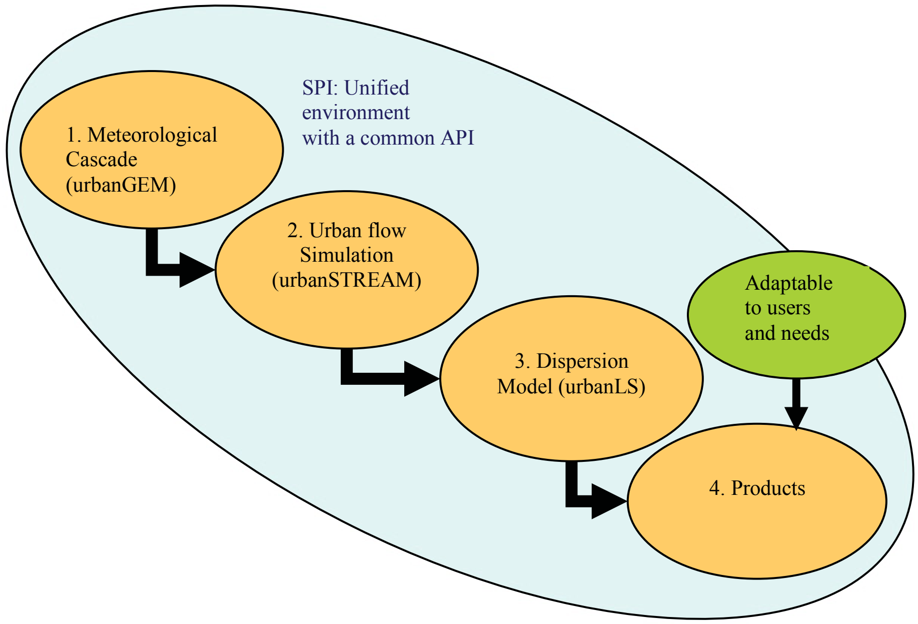

Figure 1: Schematic of the CUDM system.

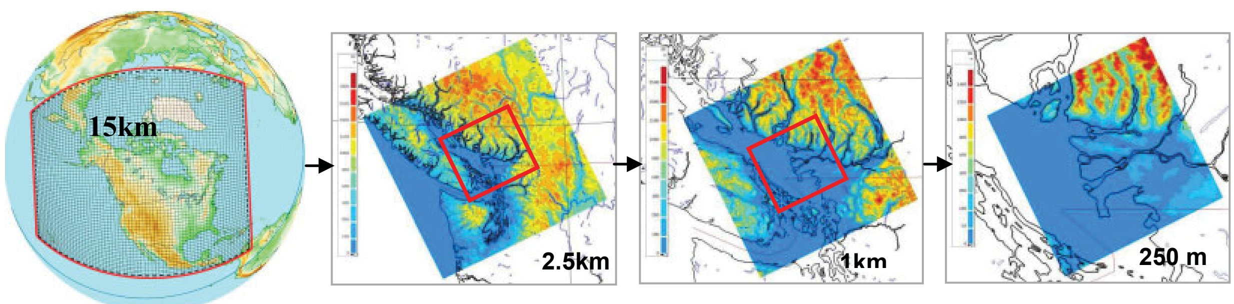

Figure 2: Nested grid domains of the meteorological (NWP) cascade used over Vancouver during the 2010 Winter Olympics and Paralympics. On the left, the operational regional model grid covered North America at a horizontal resolution of 15 km. This model provided inflow boundary conditions to the 2.5 km operational model (second from left), which in turn fed a 1 km resolution model (second from right), which provided boundary conditions for the 250 m urbanGEM model (far right). The red boxes show the boundaries of the next higher-resolution NWP models.

4 Results

The different components of the CUDM system were combined to form a unified system, which was extensively tested over several major Canadian cities. This extensive testing allowed developing a much more reliable system, demonstrating its near-readiness for operational application, and its potential to end-users. The system was also described to a wide variety of potential users to make sure it would eventually respond to their needs. It was also an opportunity to establish contacts in view of future projects.

4.1 Transition towards operational status of the CUDM prototype

The word 'operational' has a very specific meaning for the CMC. Any new informatics system must meet a series of strict requirements to insure the integrity of CMC's production system and include: robustness, reproducibility of results, re-run ability, scientific and informatics validity, ease of maintenance and upgrades, up-to-date, relevant and accessible documentation, 24/7 support, measured and monitored performance.

The challenge was to combine different individual elements to form a truly integrated system while meeting all the CMC requirements. The challenge was even more demanding considering that the elements had been developed by different groups, using different coding standards.

In spite of these difficulties, EC-EERS was able to go successfully through all the planned steps listed in section 3.3 resulting in a much improved system that is close to an operational status. The details and results for the test periods are presented in a technical report.

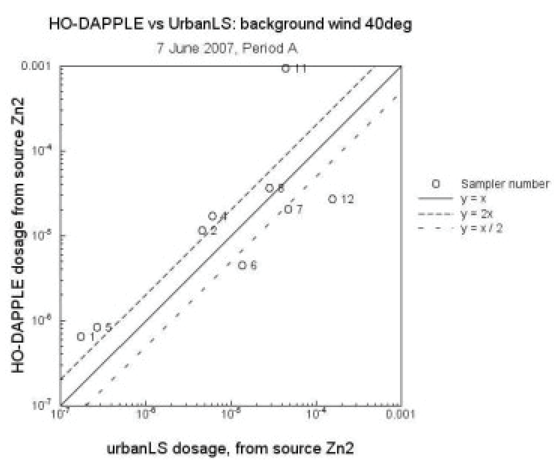

Figure 3. An example of compared dosages from the CUDM system (horizontal axis) and the observations (vertical axis) for the DAPPLE experiment of 7 June 2007. Perfect agreement between model and observation is represented by the solid sloping line.

Although, it was not a task included in the Charter, a few tests were run over London, UK, and the results compared with data from the *Dispersion of Air Pollution and its Penetration into the Local Environment* (DAPPLE) experiments, a series of urban meteorology and dispersion studies conducted by a consortium of UK universities. This is one of very few studies offering experimental data for validating urban dispersion models. The positive preliminary results (Figure 3) further confirm that the CUDM system can be applied to different cities.

4.2 Benefits of the extensive testing of the CUDM system

As anticipated, the first test period over Vancouver during the Olympics revealed a number of weaknesses of the system, which was reflected in a high failure-to-complete rate. It needs to be mentioned that many of the failures were not due to the CUDM itself, but due to significant informatics disruptions at CMC. Despite this setback, corrections and improvements were developed throughout the test periods. A dramatic improvement over time in the success rate of the full execution of the CUDM system was achieved. The final series of tests over Calgary had a 100% completion rate. Table 1 indicates the number of runs perform for each city along with their success rate. It is to be noted that the initial rate was fairly low (14%) but as the system matured the success rate reached the 100% mark. Also, all these experiments represent more than 350 different cases spread over 6 different cities and different times of the year.

While running over Toronto, a major limitation of the CUDM system was discovered. The urban flow model can not treat correctly some specific inflow wind conditions involving large divergence of the horizontal winds or large directional wind shear. A solution was proposed but did not solve the problems. This limitation will need to be addressed to render the system operational.

Table 1: Tests of the CUDM system over Canadian Cities. The rightmost column shows the success rate of the full execution of the system, *i.e.* from NWP to dispersion model output.

City	Period	Number of Successful Runs (Total)	Completed executions of CUDM
Vancouver	12 Feb-8 Mar, 2010	7 (49)	14%
Vancouver	12-26 March, 2010	15 (34)	44%
Toronto	25 June-25 Aug,2010	86 (98)	88%
Montréal	21 Aug-21 Sept, 2011	29 (32)	91%

Ottawa	29 Sept-11 Nov, 2011	48 (50)	96%
Winnipeg	24 Nov-19 Dec, 2011	26 (26)	100%
Calgary	28 Nov 2011-9 Feb 2012	40 (40)	100%
Calgary	24 Feb-19 March, 2012	24 (24)	100%

4.3 New Capabilities and Partnerships

The EC-EERS team made many efforts to participate in national-to-local response exercises and organize meetings to demonstrate the benefit of an urban dispersion modelling system such as the CUDM system running in a national centre such as CMC.

EC-EERS organized several meetings (detailed below) to establish contacts, understand the needs of participants, and to describe to participants the CUDM system, showcasing it in a potential operational role. A specific priority was to develop a basic set of guidance products and product dissemination methods.

LIST OF MEETINGS:

November 2010

Federal representatives from EC-Emergency Science and Technology Section, EC-Environmental Protection Operation Directorate, Health Canada-Radiological Protection Bureau.

January 2011

Representatives from the following organizations were present:

CPIQ : Centre de Prévision des Intempéries du Québec, Montréal (EC-SMC)
CSC : Centre de Sécurité Civile, Ville de Montréal
DAPE : Direction des activités de protection de l'environnement, Montréal (EC)
EC : Environnement Canada
MSP : Ministère de la Sécurité Publique du Québec
SSIM : Service de sécurité incendie de Montréal

April 2011

Another meeting was organized on 18 April 2011 with several representatives from the Department of National Defense (DND)'s Canadian Joint Incident Response Unit (CJIRU). The CUDM prototype was described in detail, and potential operational applications were discussed. CJIRU representatives expressed interest in the modeling capabilities of EC-EERS in potential

support of their activities. CJIRU and EC-EERS both have similar requirements for operational readiness.

October 2011

Meeting with representatives from DND Joint Meteorological Centre.

November 2011
Second meeting with CJIRU representatives

May and October 2012

Meeting with Royal Canadian Mounted Police representatives.

Information from these meetings will guide the future development of the system.

5 Transition and Exploitation

As stated previously, the objective of this project was to transition an urban flow and dispersion modeling system from an R&D mode towards a quasi-operational mode. This transition was made possible by developing advanced modeling capabilities and the required infrastructure, and by running the new prototype over several Canadian cities in collaboration with several users. The system was run in a quasi-operational mode within the CMC informatics infrastructure. At the end of the project, the modelling components were integrated within the required infrastructure to form a near operational system: the CUDM system.

In its actual configuration, the CUDM system is at a TRL of 7. Another project is needed to increase the TRL to 9, which will enable EC-EERS to provide specialized guidance for response in the event of actual atmospheric toxic releases affecting the main Canadian cities and to provide modeling support for planning and risk-assessment mode.

As mentioned previously, a major limitation of the CUDM system was discovered, namely the urban flow model can not process some particular inflow wind conditions. A solution to that limitation was tested but could not solve the problems. Also, the urban flow model version currently used in the CUDM prototype can not take into consideration the effects of orography, which is seen as a major limitation. A specific module was developed and tested to this end but its incorporation into the prototype was outside the scope of this project.

A fully operational system will need to be able to deal with any type of inflow conditions and take into consideration the effects of orography. An operational system would also benefit from optimization of the urban model code, adaptation of the existing meteorological cascade mechanics, and a sophisticated graphical interface to access urban capabilities. The resulting CUDM system will eventually provide EC-EERS with the key-enabling technology to demonstrate its capability as a primary national reach-back and support centre for CBRN planning, real-time assessment, and emergency response in Canada.

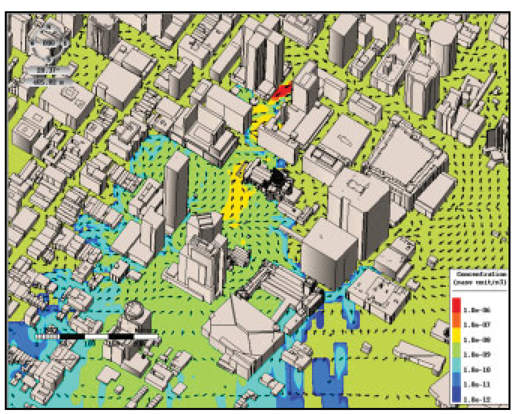

Figure 4: Example of CUDM ground-level wind vector fields together with 30-minute-averaged concentration, over downtown Montreal. Higher concentrations are represented by warmer colours. The inflow wind was from the northwest (upper left).

6 Conclusion

This project was a success; the transition of a state-of-the-science urban flow and dispersion modeling system towards the status of a functional operational system prototype at EC-EERS was completed. This was accomplished within the allocated budget and with only manageable delays.

The CUDM system is the only quasi-operational system that can generate CBRN dispersion modeling products at the building-resolving scale. These products have the potential to provide guidance in support of pre-event scenario preparedness planning, response, and post-event assessment for CBRN events.

This was accomplished by completing three major tasks, (1) providing additional advanced modeling capabilities, (2) developing the required supporting infrastructure, and (3) combining all the components in a quasi-operational computing environment and demonstrating the performance and applicability of the new operational system prototype.

All tasks were completed according to the Charter. The CUDM system, a quasi-operational prototype, was installed at EC-EERS and run over several Canadian cities for extended periods of time (see Table 1). Running the system over such a wide variety of meteorological conditions was the only way to identify a number of deficiencies. Most of these were corrected resulting in a much more robust system. However, the problem related to complex inflow conditions will need to be solved in a follow-up project.

Decision makers and emergency management officers were involved throughout the course of the project to make sure the new system would meet their operational needs. It was also a way to build a network of contacts in the urban dispersion world. This network will be instrumental to the success of a follow-up project to install and run a truly operational CUDM system.

The different components of the CUDM system were developed and validated using results from the Oklahoma City Joint Urban 2003 field campaign. The CUDM prototype was also tested with success against data from DAPPLE (Dispersion of Air Pollution and its Penetration into the Local Environment), further confirming the general application of the system.

We are convinced that the CUDM system will fill an important gap in atmospheric dispersion in the urban environment in Canada. To achieve this, the following additional work is needed: full integration of the urban capabilities in the operational CMC suite, integration of a capability to treat complex inflow conditions, integration of orographic capabilities, and development of tools to rapidly initiate an operational response. This third project would complete the endeavour started with CRTI 02-0093RD, which produced the main components of the CUDM system, and followed by this project (CRTI 07-0196TD) which produced a quasi-operational prototype.

7 Project Team

The project was initially managed under the leadership of Mr. Richard Hogue, Director, National Prediction Operations, Weather and Environmental Prediction and Services Directorate, Canadian Meteorological Center, Meteorological Service of Canada, Environment Canada. Pierre Bourgouin, now Chief, Environmental Emergency Response Section (EC-EERS) also under National Prediction Operations, Weather and Environmental Prediction and Services Directorate took over in September 2010.

The team of research scientists at Environment Canada (EC)'s Recherche en Prévision Numérique (RPN), Drs. Stéphane Bélair and Jocelyn Mailhot, led the work on the aspects related to the urbanized meteorological model as well as on the coupling with the CFD model.

Mr. Amin Erfani, acting Chief of CMC's Numerical Weather Prediction (NWP) Section and Nathalie Gauthier, led the work related to the technology transfer process of the urbanized meteorological model. They worked closely with the RPN researchers on the development of the improved NWP modeling system.

Dr. Eugene Yee of DRDC-Suffield completed the work on source reconstruction and worked with Dr. Fue-Sang Lien of WatCFD towards the improvement of the CFD model.

The Environmental Emergency Response Section (EC-EERS) at CMC played a key role in all aspects related with the implementation and execution of the modeling prototype, as well as aspects related with the user community. Furthermore, the team implemented source term modules for various release scenarios and will ensure efficient linkages with HC's Radiation Protection Bureau (RPB) for RN issues. They worked on the development of guidance products such as for the generation of impact type products (ERPG, IDLH, etc.) and examined various product dissemination methods including web-mapping technologies. The following colleagues within the team participated to various degrees in project, bringing on board a large set of expertise: Dr. Najat Benbouta (CFD modeling and implementation issues), Mr. Nils Ek, Pierre Bourgouin and Calin Zaganescu (dispersion modeling, implementation and operational response issues, CFD modeling), Mr. Alexandre Leroux (geomatics expertise and supporting databases), Mr. Serge Trudel, Gilles Mercier and Jean-Philippe Gauthier (informatic issues, visualisation tools, data exchange).

Other project partners include:

Mr. Patrick Lambert, the Head of the Field and Response Section of Environment Canada's Emergencies Science and Technology Division (ESTD), has extensive experience in interacting with the emergency response user community. Mr. Lambert and his colleagues at ESTD, as well as with Environment Canada's regional centers, will be evaluating the modeling products from a user's perspective and providing advice and feedback from the first responder community.

Mr. Stéphane Grenon is the head of the EC's Quebec Region Environmental Emergency Section. Mr. Grenon leads a very dynamic and highly trained operational response group which is strongly involved with the first responder community. His group will play a key role in testing and

demonstrating the capabilities of the modeling prototype and will bring much needed practical feedback to the project team.

Mr. Éric Pellerin is the Acting Head of the Technical Assessments Coordination Section of the Nuclear Emergency Preparedness and Response at Health Canada's Radiation Protection Bureau (RPB). His team plays a key role in the FNEP (Federal Nuclear Emergency Plan). Mr. Pellerin will be involved both from a user's perspective by providing advice and feedback, as well as from a developer's perspective by evaluating various options available for integrating the urban modeling products into RPB's ARGOS system for support of FNEP.

Lieutenant (Navy)_Derrell Benoit is the Nuclear Emergency Response Team Leader at CFB-Halifax Base Operations and has many years of experience as a CBRN Defence specialist. Mr. Becker and his colleagues at CFB Halifax Base, which is in Halifax harbor, will bring to the team a unique user's perspective and will be providing advice and feedback on the modeling products and participating at the consultations with local EMO responders.

The collaborators on this team have complementary expertise and are drawn from both the R&D (academic, industrial, and government) sectors and operational (government operations centre) environments. The development of the operational urban modeling system for EC-EERS in this project benefits from the tight coupling of R&D and operations in the sense that operational needs drive the R&D objectives and R&D results directly benefit operations.

8 Project performance summary

Technical Performance Summary:

Another project is needed to increase the TRL to 9, which will enable EC-EERS to provide specialized guidance for response in the event of actual atmospheric toxic releases affecting the main Canadian cities and to provide modeling support for planning and risk-assessment mode.

The urban modelling system developed during the previous CRTI project (02-0093RD) was at a TRL of 6 as it was validated with data from the Intensive Observation Period Six (IOP6) of the Joint Urban 2003 Oklahoma City field experiment over a relatively small number of cases, and under near ideal conditions (flat terrain, rectilinear street pattern, winds aligned with streets, relatively small down-town centre, uniform surface). The system prototype was demonstrated in an operational environment over a large number of cities and for extended periods of time. The conditions over the Canadian cities departed from the ideal conditions found over Oklahoma City. It is estimated that the work done during this project on the CUDM system elevated its TRL to 7. As mentioned, several problems were identified and solved but the prototype has not reached its final form. As is, it is not fully ready for implementation in an operational environment. This achieves the objective which was to develop a quasi-operational prototype. A new proposal to bring the CUDM prototype to a TRL of 9 upon completion of a 3-year project was submitted to CSSP in December 2012.

Toxic releases are possible everywhere in Canada, especially in major cities, where a large fraction of the Canadian population lives. In Canada, there are currently no capabilities to accurately model in an operational 24/7 context the evolution of toxic clouds in the complex urban environment. The addition of the urban capability into EC-EERS will therefore address a major gap by operationally providing high-fidelity dispersion guidance for major Canadian cities. This capability will not only significantly contribute to improved real-time responses but will also provide scientific guidance for activities such as pre-event planning, including scenario-based activities, post-event recovery and clean-up.

Schedule Performance Summary:

Only minor modifications to completion dates of a few milestones were needed during the course of the project. These modifications were mainly related to unexpected unavailability of personnel (external assignment, delays related to replace a departure) and to scientific or technical difficulties to complete a few milestones.

Cost Performance Summary:

The project was completed without exceeding the original allocated total CRTI funds. However, some fund transfers were needed from 2008/09, 2009/10 and 2010/11 towards 2011/12 and 2012/13 to deal with unexpected delays and unavailability of personnel.

9 Publications, Presentations, Patents

9.1 Technical reports

Benbouta, N, Bourgouin, P., Ek, N.(2013), Canadian Urban Dispersion Modeling System (CUDM) – Tracking and predicting the Atmospheric Dispersion for Hazardous Material Releases in Urban Environments. CRTI Project 07-0196TD Internal Technical Report. Environmental Emergency Response Section, Environment Canada.

Meishen Li, Kun-Jung Hsieh, Hua Ji and Fue-Sang Lien (2012), "Development and Implementation of Advanced Modeling Capabilities in Support of "Towards an Operational Urban Modeling System for CBRN Emergency Response and Preparedness" ", Final Report, Waterloo CFD Engineering Consulting Inc.

Yee, E. (2010), "An Operational Implementation of a CBRN Sensor-Driven Modeling Paradigm for Stochastic Event Reconstruction - Technical Description of an Advanced Modeling Component of CRTI Project 07-0196TD", DRDC Suffield TR 2010-070.

Yee, E., Lien, F.S. and Ji, H. (2010), "A Building-Resolved Wind Field Library for Vancouver Facilitating CBRN Emergency Response for the 2010 Winter Olympic Games", DRDC Suffield TM 2010-088.

Yee, E., Lien, F.S. and Ji, H. (2007), "Technical Description of Urban Microscale Modelling System: Component 1 of CRTI Project 02-0093RD, DRDC Suffield TR 2007-067.

9.2 Publications in peer-reviewed scientific journals

Hsieh, K.J.,, F.S. Lien and E. Yee (2007), "Numerical Modelling of Scalar Dispersion in an Urban Canopy", *Journal of Wind Engineering & Industrial Aerodynamics*, Vol. 95, pp. 1611-1636.

Hsieh, K.J., Lien, F.S. and Yee, E. (2010), "Towards a Unified Turbulence Simulation Approach for Wall-Bounded Flows", *Flow, Turbulence and Combustion*, 84, 193-218.

Husain, S.Z., S. Bélair, S. J. Mailhot, and S. Leroyer, 2012: Improving the representation of nocturnal near-neutral surface layer in urban environments with a mesoscale atmospheric model. Conditionally accepted for publication in Boundary Layer Meteorology.

Husain, S.Z., S. Bélair, J. Mailhot, and S. Leroyer, 2012: Influence of soil moisture on urban microclimate and surface layer meteorology in Oklahoma City. To be submitted in Boundary Layer Meteorology.

Ji, H., F.S. Lien and E. Yee (2008), "A Robust and Efficient Hybrid Cut-Cell/Ghost-Cell Method with Adaptive Mesh Refinement for Moving Boundaries on Irregular Domains", *Computer Methods in Applied Mechanics and Engineering*, Vol. 198, pp.432–448

Ji, H., Lien, F.S. and Yee, E. (2010), "A New Adaptive Mesh Refinement Data Structure with an Application to Detonation", *Journal of Computational Physics*, 229, 8981-8993.

Keats, A., Yee and F.S. Lien (2007), "Bayesian Inference for Source Determination with Applications to a Complex Urban Environment", *Atmospheric Environment*, Vol. 41, pp. 465-479.

Keats, A., E. Yee and F.S. Lien (2007), "Reply to the 'Comments on: 'Bayesian Inference for Source Determination with Applications to a Complex Urban Environment'", *Atmospheric Environment*, Vol. 41, pp. 5547-5551.

Keats, A., M.T. Cheng, E. Yee and F.S. Lien (2009), "Bayesian Treatment of a Chemical Mass Balance Receptor Model with Multiplicative Error Structure", *Atmospheric Environment*, Vol. 43, pp. 510-519.

Keats, A., M.T. Cheng, E. Yee and F.S. Lien (2009), "Bayesian Treatment of a Chemical Mass Balance Receptor Model with Multiplicative Error Structure", *Atmospheric Environment*, Vol. 43, pp. 510-519.

Lemonsu, A., S. Bélair, J. Mailhot, M. Benjamin, F. Chagnon, G. Morneau, B. Harvey, J. Voogt, and M. Jean, 2008: Overview and First Results of the Montreal Urban Snow Experiment 2005, *J. appl. Meteorol and climatol.*, 47, 59-75.

Lemonsu, A., S. Bélair, and J. Mailhot, 2009: The New Canadian Urban Modeling System: Evaluation for Two Cases from the Joint Urban 2003 Oklahoma City Experiment, *Boundary-Layer Meteorol*, 133, 47-70.

Lemonsu, A., S. Bélair, J. Mailhot and S. Leroyer, 2010: Evaluation of the Town Energy Balance Model in Cold and Snowy Conditions during the Montreal Urban Snow Experiment 2005, *J. appl. Meteorol and climatol.*, 49, 3, 346-362.

Leroux, A., A. Lemonsu, J.-P. Gauthier, S. Bélair, and J. Mailhot, 2009: Automated urban land use and land cover classification for mesoscale atmospheric modeling over Canadian cities. *Geomatica*, **63**, 13-24.

Leroyer, S., J. Mailhot, S. Bélair, A. Lemonsu, and I. Strachan, 2010: Modeling the surface energy budget during the thawing period of the 2006 Montreal Urban Snow Experiment. *J. Appl. Met. Climatol.*, **49**, 68-84.

Leroyer, S., S. Bélair, J. Mailhot, and I.B. Strachan, 2011: Microscale numerical prediction over Montreal with the Canadian external urban modeling system. *J. Appl. Meteor. Climatol.*, **50**, 2410-2428.

Leroyer, S., S. Bélair, J. Mailhot, S.Z. Husain, 2012: Sub-kilometric Numerical Weather Prediction in an Urban Coastal Area: A case study over the Vancouver Metropolitan area during the EPiCC experiment. To be submitted in J. Appl. Meteor. Climatol.

Lien, F.S, E. Yee, H. Ji and K.J. Hsieh* (2008) "Partially Resolved Numerical Simulation and RANS Modeling of Flow and Passive Scalar Transport in an Urban Environment", Special Issue of *Journal of Wind Engineering & Industrial Aerodynamics*, Vol. 96, pp. 1832-1842.

Wang, B.C., E. Yee and F.S. Lien (2009), "Numerical Study of Dispersing Pollutant Clouds in a Built-up Environment", *Int. J. Heat Fluid Flow*, Vol. 30, pp. 3-19.

Yee, E., F.S. Lien, A. Keats* and R. D'Amours (2008), "Bayesian Inversion of Concentration Data: Source Reconstruction in the Adjoint Representation of Atmospheric Diffusion", Special Issue of *Journal of Wind Engineering & Industrial Aerodynamics*, Vol. 96, pp. 1805-1816.

Yee, E., B.C. Wang, F.S. Lien (2009), "Probabilistic Model for Concentration Fluctuations in Compact-Source Plumes in an Urban Environment", *Boundary-Layer Meteorology*, Vol. 130, pp. 169-208.

9.3 Proceedings, Presentations at Conferences and Symposium

Abrahamowicz, M., S. Bélair, S. Leroyer, N. Gauthier, S.Z. Husain, J. Mailhot, and A. Lemonsu, 2010: Snow, Vegetation and Asymmetric Canyons in the Canadian Version of the Town Energy Balance (TEB) Urban-Canopy Scheme, *9th Symposium on the Urban Environment*, 2-6 Aug, Keystone, CO, USA.

Bélair, S., M. Abrahamowicz, S. Leroyer, E. Christensen, Y.-C. Chung, A. Lemonsu, J. Maihot, I. Strachan, 2009: Evolution of snow packs in the Town Energy Balance (TEB) model, based on results at EPiCC rural, suburban, and urban sites, Proc*, 7th International Conference of Urban Climate*, 29 June- 3 July, Yokohama, Japon, A12-3 .

Bélair, S., M. Abrahamowicz, S. Leroyer, N. Bernier, N. Gauthier, and A. Leroux, 2011: Sub-km External Surface Modeling to Improve Fluxes over Ecosystems, Cities, and Water Surfaces in Numerical Predictions Systems, *3rd integrated Land Ecosystem-Atmosphere Processes Study iLEAPS International Science Conference,* 18-23 Sept., Garmisch-Partenkirchen, Germany.

Bélair, S., M. Abrahamowicz, S. Leroyer, N. Bernier, N. Gauthier, V. Souvanlasy, A. Leroux, J.-P. Gauthier, 2012: Sub-km external surface modeling to improve numerical predictions over ecosystems, cities, and water surfaces. Annual Meeting of the Canadian Meteorological Society and Numerical Weather Prediction Conference of the American Meteorological Society, 29 May to 1 June 2012, Montreal, Canada (oral presentation by S. Bélair)

Bélair, S., S. Leroyer, S.Z. Husain, J. Mailhot, M. Abrahamowicz, and N. Benbouta, 2012: Urban modeling in support to numerical weather prediction and emergency response at Environment Canada. Preprint for International Symposium on Extreme Weather and Cities, Tokyo, Japan, 23-24 October 2012.

Bélair, S., S. Leroyer, S. Husain, J. Mailhot, M. Abrahamowicz, and N. Benbouta, 2012: Urban modeling in support to numerical weather prediction and emergency response at Environment

Canada. Symposium on Extreme Weather and Cities, Tokyo, 23-24 October 2012 (invited oral presentation by S. Bélair).

Bourgouin, P., N. Benbouta,, S. Bélair, R. Hogue, N. Gauthier, E. Yee, F.-S. Lien, and co-authors, 2012: The development of a prototype of a Canadian Urban Flow and Dispersion Modeling System.. Annual Meeting of the Canadian Meteorological Society and Numerical Weather Prediction Conference of the American Meteorological Society, 29 May to 1 June 2012, Montreal, Canada (oral presentation by P. Bourgouin).

Husain, S.Z., S. Bélair, S. Leroyer, N. Gauthier, M. Abrahamowicz, and J. Mailhot, 2011 : Improving the Representation of Surface Exchanges between the Urban Canopy and the Surface Layer in a Mesoscale Atmospheric Model, *20th Conference on Numerical Weather Prediction*, 23-27 Jan, Seattle, WA, USA.

Husain, S.Z., Bélair, S., Gaudreault, S. and Mailhot, J., 2010 : Improving Surface-Layer Forecasting in Urban Environments with a Mesoscale Atmospheric Model, *9th Symposium on the Urban Environment*, 2-6 Aug, Keystone, CO, USA.

Husain, S., S. Bélair, J. Mailhot, S. Leroyer, M. Abrahamowicz, and N. Gauthier, 2012: Improving urban surface layer forecasting in a mesoscale atmospheric model. 8th International Conference on Urban Climate and 10th Symposium on the Urban Environment, 6-10 August 2012, Dublin, Ireland (oral presentation by S. Husain).

Lemonsu, A., A. Leroux, S. Bélair, S. Trudel, and J. Mailhot, 2006: A General Methodology of Urban Cover Classification for Atmospheric Modeling. Preprints, *6th Symposium on the Urban Environment*, 2-6 Aug, Atlanta, GA, USA.

Lemonsu, A., S. Bélair,J. Mailhot and S. Leroyer, 2009: Evaluation of the TEB model under cold and snowy conditions for the Montreal Urban Snow Experiment (MUSE) 2005, Proc, *7th International Conference of Urban Climate*, 29 June- 3 July, Yokohama, Japon, A12-6 .

Lemonsu, A., S. J. Mailhot and S. Leroyer, 2009: Evaluation of the TEB model under cold and snowy conditions for the Montreal Urban Snow Experiment (MUSE) 2005, *8th AMS Symposium on the Urban Environment, Phoenix*, Ar, 11th-15th Jan, J9.3 .

Leroyer, S., J. Mailhot, S. Bélair, A. Lemonsu and I. B. Strachan, 2009: The Urban Surface Energy Budget during the early spring period of the Montreal Urban Snow Experiment (2006), *8th AMS Symposium on the Urban Environment*, Phoenix, Ar, 11th-15th January 2009, J9.4 .

Leroyer, S., J. Mailhot, S. Bélair and I. B. Strachan, 2009: The Canadian urban off-line modeling system applied on the Montreal metropolitan area: which benefits for weather forecasting and Urban Heat Island evaluation ?, *7th International Conference of Urban Climate*, 29 June- 3 July, Yokohama, Japon, A12-5 .

Leroyer, S., J. Mailhot, S. Bélair, A. Lemonsu and I. B. Strachan, 2009: Influence of the thermal roughness length parametrization in the TEB scheme on the simulation of the surface energy budget during the thawing period of the Montreal Urban Snow Experiment (2006), *7th International Conference of Urban Climate*, 29 June- 3 July, Yokohama, Japon, P3-27 (*poster*).

Leroyer, S., S. Bélair, J. Mailhot, and I. B. Strachan, 2010 : Off-line Numerical Weather Prediction over Montreal with the Canadian Urban Modeling System, *9th Symposium on the urban environment*, 2-6 Aug, Keystone, CO, USA.

Leroyer, S., S. Bélair, J. Mailhot, 2011 : The Canadian external urban and land surface modeling system: Summertime evaluation over the Montreal metropolitan area, *10th European Conference on Applications of Meteorology*, 12-16 Sept, Berlin, Germany.

Leroyer, S., S. Bélair, J. Mailhot, 2011, S.Z. Husain, N. Gauthier, 2011: High-Resolution Numerical Simulations over the Complex Urban Area of Vancouver, Canada, *10th European Conference on Applications of Meteorology*, 12-16 Sept, Berlin, Germany.

Leroyer, S., S. Bélair, J. Mailhot, 2011 : Numerical Simulations of the influence of the Vancouver metropolitan area on summertime atmospheric circulations during EPiCC, *20th Conference on Numerical Weather Prediction*, 23-27 Jan, Seattle, WA, USA.

Leroyer, S., S. Bélair, M. Abrahamowicz, N. Gauthier, A. Leroux, V. Souvanlasy, and J. Mailhot, 2012: Microscale Numerical Prediction over Cities in Southern Ontario, Canada. *8th International Conference on Urban Climate and 10th Symposium on the Urban Environment*, 6-10 August 2012, Dublin, Ireland (poster presentation by S. Leroyer).

Leroyer, S., S. Bélair, and J. Mailhot, and S Z Husain, 2012: Sub-km numerical simulations over a coastal area. *8th International Conference on Urban Climate and 10th Symposium on the Urban Environment*, 6-10 August 2012, Dublin, Ireland (oral presentation by S. Leroyer).

Voogt, J. A., T. R. Oke, O. Bergeron, S. Leroyer, B. Crawford, E. Christensen, B. Nanni, T. R. Tooke, D. van der K., F. Chagnon, 2009: The environmental prediction in Canadian cities (EPiCC) network. *Proc, 7th International Conference of Urban Climate*, 29 June- 3 July, Yokohama, Japon, P2-44 (poster).

9.4 Refereed Conference Proceedings

Hogue, R., N. Benbouta, S. Belair, J. Mailhot, E. Yee, F.S. Lien and J.D. Wilson (2009), "The Development of a Prototype of a Canadian Urban Flow and Dispersion Modeling System", *Proc. 8th Symposium on Urban Environment (the 89th American Meteorological Society Annual Meeting)*, January 10-15, Phoenix, USA.

Ji, H., F.S. Lien and E. Yee (2008), "A New Cartesian Grid Method with Adaptive Mesh Refinement for Degenerate Cut Cells on Moving Boundaries", *Proc. 5th Int. Conf. On Computational Fluid Dynamics*, July 7-11, Seoul, Korea

Wang, B.C., E. Yee and F.S. Lien (2009), “Numerical Modeling of Concentration Fluctuations for Pollutant Dispersion in an Urban Area”, *Proc. 6th International Conference on Computational Heat and Mass Transfer*, May 18-21, Guangzhou, China.

Wang, B.C., E. Yee and F.S. Lien (2009), “Modeling Concentration Fluctuations from a Localized Source in Complex Urban Turbulent Flow”, *Proc. 6th International Symposium on Turbulence and Shear Flow Phenomena*, June 22-24, Seoul, Korea.

9.5 Conference Proceedings:

Bourgouin, P., The Canadian Meteorological Centre’s integrated emergency response system for modeling atmospheric transport and dispersion of pollutants. *American Meteorological Society (AMS) 16th Conference on Air Pollution Meteorology* Atlanta, Georgia, 20 January 2010.

Bourgouin, P., The Canadian Urban Dispersion Modeling (CUDM) System: Prototype Evaluation over Vancouver 2010. *31st NATO/SPS International Technical Meeting on Air Pollution Modelling and its Application*. September 2010.

Bourgouin, P., Ek, N., Gauthier, J.P., Hogue, R., Leroux, A., Mercier, G., Trudel, S., Zaganescu, C., The Canadian Urban Dispersion Modelling (CUDM) System: Possible Operational Uses, *CUDM End-User Meeting at Canadian Meteorological Centre*, 10 November 2010.

Bourgouin, P., Project: CRTI 07-0196TD *(2009-2012)* Towards an Operational Urban Modeling System for CBRN Emergency Response and Preparedness. *CRTI Summer Symposium*. June 2012.

Ek, N., The Canadian Urban Dispersion Modelling System: An Operation Prototype. *34th Arctic Marine Oilspill Programme (AMOP) Technical Seminar on Environmental Contamination and Reponse*, Banff, Alberta, 5 October 2011.

Hogue, R., The development of a prototype of a Canadian urban flow and dispersion modeling system. AMS, *8th Symposium on the Urban Environment*, 14 January 2009.

Yee, E., On the Reconstruction of Arbitrary Source Distributions Using a Bayesian Probabilistic Inferential Framework, *Thirteenth International Conference on Harmonization Within Atmospheric Dispersion Modelling for Regulatory Purposes*, Unclassified, Paris, France, 5 pp., 2010.

List of symbols/abbreviations/acronyms/initialisms

API:	Application Programming Interface.
CBRN:	Chemical, Biological, Radiological or Nuclear.
CFD:	Computational Fluid Dynamics.
CMC:	Canadian Meteorological Centre.
CRTI:	Chemical, Biological, Radiological or Nuclear Research and Technology Initiative.
CUDM:	Canadian Urban Flow and Dispersion Model.
DAPPLE:	Dispersion of Air Pollution and its Penetration into the Local Environment
DND:	Department of National Defence.
DRDC:	Defence Research and Development Canada.
EC-EERS:	Environment Canada's Environmental Emergency Response Section.
GEM:	Global Environmental Model, CMC's operational weather forecast model.
GEMLAM:	Global Environment Model in Limited Area Model configuration
GEMREG:	Global Environment Model with Regional 15 km resolution core
IOP:	Intensive Observation Period.
ISBA:	Interaction Surface Biosphere Atmosphere, the surface land scheme.
JU03:	Joint Urban 2003 Experiment Campaign hold on June-July 2003 in Oklahoma City.
MSC:	Meteorological Service of Canada.
NWP:	Numerical Weather Prediction.
OKC:	Oklahoma City.
OPI:	Office of Primary Interest.
R&D:	Research and Development.
RPN	Recherche en Prévision Numérique.
SPC:	Storm Prediction Centre.
SPI:	Spherical Projection Interface, EC-EERS viewer and programming tool.
TEB:	Town Energy Balance scheme, used in urbanized GEM numerical model.
WMS:	Web Map Service.